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PROSPECTIVE MEMORY IN DYNAMIC ENVIRONMENTS: EFFECTS OF LOAD, DELAY, AND PHONOLOGICAL REHEARSAL

Maria Stone, Key Dismukes, and Roger Remington

NASA-Ames Research Center

Address Correspondence to:

Key Dismukes

Mail Stop 262-4

NASA-Ames Research Center

Moffett Field, CA 94035-1000

Phone # (650) 604-0150

kdismukes@mail.arc.nasa.gov

Abstract

A new paradigm was developed to examine prospective memory performance in a visual-spatial task that resembles some aspects of the work of air traffic controllers. Two experiments examined the role of workload (number of airplanes participants directed), delay (between receipt of prospective instructions and execution), and phonological rehearsal. High workload increased prospective memory errors but increasing delay from one to three or five minutes had no effect. Shadowing aurally-presented text reduced prospective memory performance, presumably because it prevented verbal rehearsal of the prospective instructions. However, performance on the foreground task of directing airplanes to routine destinations was affected only by workload and not by opportunity for rehearsal. Our results suggest that ability to maintain performance on a routine foreground task while performing a secondary task—perhaps analogous to conversation—does not predict ability to retrieve a prospective intention to deviate from the routine.

Prospective Memory in Dynamic Environments: Effects of Load, Delay, and Phonological Rehearsal.

Prospective memory is defined as remembering to remember – remembering and executing delayed plans with no additional prompts at the time of intended retrieval (Brandimonte, Einstein, & McDaniel, 1996; Guynn, McDaniel, & Einstein, 1998; Koriat, Ben-Zur, & Nussbaum, 1990; Kvavilashvili 1987). Prospective memory tasks can be created in the laboratory by instructing subjects to make a special response to a specific event (event-based) or at a specific time (time-based) while they are otherwise engaged in a different task. For example, in the event-based prospective memory paradigm of Einstein and McDaniel (1990), participants are engaged in a foreground[1] cover task such as rating the pleasantness of words or memorizing word lists for short-term recall. They are also given a prospective task, typically to press a key when they encounter a particular word or category of word in the cover task. Variations of the Einstein-McDaniel paradigm have been used by several research groups to explore cognitive processes underlying prospective memory (e.g., Brandimonte & Passolunghi, 1994; Einstein, Holland, McDaniel, & Guynn, 1992; Einstein, Smith, McDaniel, & Shaw, 1997; Marsh & Hicks, 1998; McDaniel & Einstein, 1993; Otani, Landau, Libkuman, St. Louis, Kazen & Throne, 1997).

Prospective memory is not confined to the laboratory, but is common in daily life. Indeed, several naturalistic studies of prospective memory have used everyday tasks (e.g., Ceci & Bronfenbrenner, 1985; Walbaum, 1997; Sellen, Louie, Harris, & Wilkins, 1997; Meacham & Leiman, 1982). Failures of prospective memory are not uncommon and the resulting errors can have dramatic consequences in workplace settings such as medicine, nuclear power plant operations, and aviation. For example, in 1991 a tower controller at Los Angeles airport cleared an airplane to position and hold on runway 24 left (a standard procedure), intending to release the airplane for takeoff as soon as she was able to arrange for another airplane to cross the runway at the far end. The controller was quite busy managing multiple aircraft and making frequent radio transmissions – as is typical at busy airports – and several inadvertent delays occurred. Visibility was poor in the twilight haze, and glare was present from numerous light sources. Forgetting that she had not cleared the holding airplane to depart, the controller cleared an arriving airplane to land on runway 24 left, which it did, crashing into the holding airplane, and killing a number of passengers and crew (National Transportation Safety Board, 1991).

Both real life and laboratory examples (e.g., Einstein & McDaniel, 1990) illustrate three key features of prospective memory. The conjunction of these three features distinguishes prospective memory tasks from traditional studies of retrospective memory. First, prospective memory lacks any explicit prompt to perform the required memory retrieval. Thus, in a laboratory paradigm, when a target word appears in the course of a foreground cover task the participant must retrieve and execute the prospective instruction without prompting. Second, prospective memory involves a delay between the formation of an intention and the opportunity to carry it out, created by the necessity to emit the response to the prospective task only in the presence of a signal event (event-based) or during a specified temporal window (time-based). The air traffic controller in the preceding example was not immediately able to clear the aircraft for takeoff, but had to defer that intention until other aircraft were out of the way. Third, prospective memory intrinsically involves concurrent-task performance. While performing foreground task activities with their associated cognitive demands, the individual must, in response to the appropriate cue, retrieve the prospective intention, interrupt the foreground task, and execute the intention. However, in contrast to most dual-task paradigms, one of the tasks is deferred for some period before execution. (See Ellis, 1996; Einstein, Smith, McDaniel, & Shaw, 1997; and Maylor, 1993 for other discussions of the defining characteristics of prospective memory).

These characteristics – uncued recall, deferred intention, and concurrent task loading – are associated with demands on working memory, suggesting that prospective memory places considerable demands on working memory. There is general agreement that working memory (Baddeley & Hitch, 1994; Baddeley & Logie, 1999; Becker, 1994; Gathercole, 1994; Goldman-Rakic, 1987; Martin & Romani, 1994) is a multi-component psychological system that supports the temporary storage of internal representations that guide and control action during performance of cognitively complex tasks. In one of the most widely cited formulations, working memory relies on several modality-specific immediate memory systems overseen by a central executive (Baddeley & Logie, 1999; Goldman-Rakic, 1987), or Supervisory Attentional System (SAS) (Norman & Shallice, 1980). Baddeley and Logie (1999) describe two modality specific slave systems: a phonological loop, for the temporary storage of auditory information, and a visual-spatial scratch pad, for the temporary storage of visual-spatial information.

Several recent studies have implicated working memory in prospective memory performance, however the involvement appears complex. Dividing attention at retrieval by requiring participants to monitor a series of auditorally presented digits for the occurrence of two or three consecutive odd digits reduced prospective memory performance (Einstein, McDaniel, Smith, & Shaw, 1998; McDaniel, Robinson-Riegler, & Einstein, 1998). In contrast, Otani et al. (1997) found no effect on prospective memory when attention was divided by having participants continuously repeat the word 'the' or a series of digits.

These contrasting findings might be explained by differences in the nature of the concurrent task used to divide attention. Monitoring for consecutive odd numbers probably draws especially upon executive resources whereas the articulatory suppression used by Otani et al. probably affected the phonological loop preferentially. To resolve this issue, Marsh and Hicks (1998) divided attention systematically with a series of tasks chosen to load executive resources, the phonological loop, or the visual-spatial sketchpad preferentially. They found that prospective memory performance declined with increasing load on executive resources but was not affected by articulatory suppression or by selective loading of the visual-spatial sketchpad. Consistent with the analysis of Marsh and Hicks, several studies in the cognitive aging literature have found prospective memory is impaired with age under conditions in which the foreground task places substantial demands on working memory (Cherry & LeCompte, 1999; Einstein et al, 1997; Kidder, Park, Hertzog & Morrell, 1997; and Park, Hertzog, Kidder, Morrell, & Mayhorn, 1997).

The prospective memory literature also contains conflicting reports about the effects of retention interval on performance. Brandimonte and Passolunghi (1994) found that prospective memory performance tested three minutes after study was consistently worse than when tested immediately. Two other studies found no change in performance when the retention interval was increased from 15 to 30 minutes (Einstein, Holland, McDaniel, & Guynn, 1992) or from 4 to 20 minutes (Guynn, McDaniel, & Einstein, 1998). Hicks, Marsh, and Russell (2000) found that prospective memory actually improved over intervals of 2.5 to 15 minutes.

The complex interactions with substructures in working memory and the inconsistent effects of retention interval suggest that care be taken in extending laboratory results to complex real-world domains such as air traffic control, even though prospective memory appears to play an important role in these domains. In some real-world domains prospective memory demands occur primarily in the context of visual-spatial, rather than verbal tasks. Since it is possible that visual-spatial memory relies on separable mechanisms, the extent to which findings from the Einstein-McDaniel paradigm generalize from the verbal to the visual-spatial domain is not clear; thus, exploring prospective memory in the context of a visual-spatial task may be of both practical and theoretical significance.

Visual-spatial tasks have rarely been used in prospective memory studies, with the exception of the work of Vortac and colleagues (Vortac, Edwards, Fuller, & Manning, 1993; Vortac, Edwards, & Manning, 1995). These investigators used a task that incorporated many of the features of the work of air traffic controllers, and used a visual display similar to actual air traffic radar displays. Vortac et al. (1993) found that controllers' prospective memory performance improved, paradoxically, when the controllers were not allowed to manipulate flight data strips as they normally do to remind themselves of intentions. They also found that prospective memory performance of non-expert participants was improved by having the written prospective memory instruction available at retrieval, but not during retention (Vortac et al., 1995). These early findings have practical implications for the work of controllers, but they shed little light on the basic cognitive mechanisms underlying prospective memory in visual/spatial context and on whether or not these mechanisms are different from those underlying prospective memory in the context of verbal tasks.

In many real-world situations, in contrast to most laboratory paradigms, the prospective memory task is embedded meaningfully in the flow of foreground task activities. In one common class of situation, the individual plans to modify a habitual task sequence, for example, planning to pick up laundry on the way home from work. One of the most common forms of error is habit intrusion, in which a preoccupied person reverts to a habitual sequence of actions rather than the intended sequence (Reason, 1990). From a theoretical perspective it is desirable to explore whether intentions operate differently in the context of habitual foreground tasks.

In this paper we present a new experimental paradigm that allows prospective memory to be studied in the context of dynamic visual-spatial tasks. Participants direct moving dots representing hypothetical airplanes along a route indicated by stationary dots (waypoints). Unless otherwise instructed, participants send the airplanes along a routine (habitual) route. During the course of each trial they receive instructions to divert a small proportion of the airplanes to an alternate waypoint. The instruction to divert a specific airplane at a specific waypoint is presented on the screen and then disappears before the opportunity to execute the instruction becomes available. Note that this task satisfies the three critical characteristics of prospective memory mentioned earlier. The prospective task is embedded meaningfully in the habitual foreground task. This paradigm captures some features of air traffic control that will enable us to generalize performance across a wider range of stimulus and task conditions.

The goal of this study was to determine if working memory plays as important a role in prospective memory performance in the context of a habitual visual task as it does in the context of verbal tasks used in the Einstein-McDaniel paradigm. We examined the role of workload, verbal rehearsal, and delay on prospective memory performance.

In Experiment 1a, we manipulated the workload in terms of the number of airplanes on the screen and the delay between presentation of instruction and opportunity for execution. In Experiment 1b, we added a shadowing task (continuous repetition of an auditory message) to eliminate the opportunity for verbal rehearsal of the prospective memory instructions.

Experiment 1a

Method

Participants. Twenty-eight local community college and state university students, 18-40 years old, participated in this experiment and received credit for their participation.

Apparatus. The experiments were conducted in a soundproof booth using an IBM-PC computer.

Display. A sample display is illustrated in Figure 1. The static elements of the display were nine routine waypoints, numbered 0 through 8, and three alternative waypoints. The routine waypoints were depicted by small blue circles. Eight of these routine waypoints formed an oval arrangement in the center of the screen, and the remaining (exit) waypoint was in the upper right corner of the screen. The arrangement in the center of the screen was 14.5 cm across and 13.5 cm vertically. The remaining waypoint was positioned 1 cm from the top right corner of the screen vertically and 2 cm horizontally. Each routine waypoint was represented by a blue circle .5 cm in diameter and labeled with a number (0-8). Three of the routine waypoints had alternative waypoints associated with them (waypoints 3, 5, and 7). These alternative waypoints were represented by gray circles positioned .5 cm above (waypoint 3'), to the right (waypoint 5'), or below (waypoint 7') the corresponding routine waypoints. In addition, in the lower left corner of the screen, the size of the response window (distance from the waypoint an airplane had to reach in order to be selected for response) was indicated by a red scale. It extended from the outer edge of the circle representing the waypoint roughly one third of the distance towards the preceding waypoint.

[Figure 1 about here]

The dynamic elements of the display were green circles (.25 cm in diameter) representing hypothetical airplanes traversing the circuit of waypoints. Each was labeled with a randomly assigned capital letter of the Latin alphabet (A-Z). In the beginning of each trial, several airplanes were positioned randomly along the route of waypoints and progressed via the predetermined sequence of routine waypoints towards waypoint 8. New airplanes appeared at random intervals at waypoint 0 and moved on the same predetermined route toward waypoint 8. The algorithm for generating new airplanes was such that the number of airplanes on the screen was maintained – a new airplane appeared on the screen at random intervals within 10 s after an existing airplane disappeared at waypoint 8. Airplanes moved at a speed of three pixels per second, and took roughly 50 seconds to go from one waypoint to the next.

Task. Participants' task was to route the airplanes through the circuit of waypoints by first selecting a given airplane by positioning a pointer over the airplane and clicking a mouse when the airplane was in the response window, and then by selecting the waypoint (routine or alternate) for the airplane by positioning and clicking the mouse on the appropriate waypoint. Thus, each response consisted of two mouse responses – the first one involved selecting an airplane, and the second involved selecting the next destination waypoint for the selected airplane. For example, as airplane C approached waypoint 1, the airplane had to be selected, and to complete the response correctly, waypoint 2 (the next destination waypoint for airplane C) had to be selected. As airplane C approached waypoint 2, the airplane had to be selected again and its next waypoint (usually waypoint 3) selected.

Unless otherwise instructed, participants were to route each airplane through the sequence of routine waypoints. On every trial participants received instructions to divert three aircraft to a specified alternative waypoint. For example, if a prospective memory instruction was issued earlier to send airplane C to waypoint 3' (instead of waypoint 3), then waypoint 3' had to be selected prior to reaching waypoint 2. (Waypoints 2 and 3 were routine waypoints in our terminology, whereas waypoint 3' was an alternative waypoint). If a participant failed to select an airplane while it was in a response window, the airplane automatically continued to the next routine waypoint. Prospective memory instructions were given sequentially such that the each trial contained a 1 min, a 3 min, and a 5 min retention interval (time from when the instruction was given till when it could be carried out). Since the high load conditions contain a greater number of aircraft, the proportion of aircraft diverted differed between high and low load conditions. Our goal, however, was to equalize the prospective memory demand for the two conditions, not to balance the proportion diverted.

The following feedback was provided: If the airplane was selected correctly within the response window, it turned red and remained red until a waypoint was selected. If the airplane was not in the window for response when it was selected, participants heard a beep and the airplane remained green. After an airplane was selected, no other airplane could be selected until a waypoint was selected. Attempts to select another airplane resulted in a beep. Also, random mouse clicks not corresponding to any legitimate object resulted in a beep. No feedback was given as to the correctness of waypoint selection, and no feedback was given if participants neglected to select an airplane within the window for response.

Trial sequence. Each trial was 7 min long. Participants started a trial by pressing a key. The dynamic display appeared and the airplanes began moving. Additional airplanes appeared at waypoint 0 at random intervals. Prospective memory instructions appeared in the center of the screen in white letters. Each instruction was of the form "Reroute airplane X to #" (e.g., "Reroute airplane C to 3' "). Each prospective memory instruction remained on the screen for 10 s, and then disappeared 1 min, 3 min, or 5 min prior to when the airplane to which the instruction referred reached the appropriate window for response relevant to the instruction To execute the prospective memory instructions correctly, participants had to select the alternative waypoint for the airplane mentioned in the instruction when the airplane reached the window for response.

Each trial contained three instructions – 1 min, 3 min and 5 min delayed. To fit these three delays within the 7 min length of the trial, the periods during which the instructions operated were arranged to overlap. Thus the number of instructions participants had to keep track of varied from zero to three during the course of each trial. The order in which the instructions for the three delay periods appeared was random. There were six trials in each load condition, arranged in fixed random order for all participants. These six trials provided each of the six possible orders of the three delays. Within a given order the time of onset of each instruction was varied randomly, thus the memory demands were comparable for each of the three delays.

Design. Design was 2 x 3, with load (low, with 3 airplanes on the screen, and high, with 7 or 8 airplanes on the screen) and delay (1 min, 3 min, or 5 min) as factors potentially affecting prospective memory performance. There were six trials in each load condition, and the trials were ordered in a fixed random order for all participants.

Procedure. Each trial was initiated by a key press. After the key press, a display containing the waypoint arrangement and the initial airplanes appeared. The airplanes moved continuously for the duration of the trial. As airplanes departed the screen, additional airplanes appeared at waypoint 0. Participants directed airplanes to waypoints using the two-step response described above. The prospective memory instructions for specific airplanes appeared in the center of the screen and remained there for 10 s. Participants were told to memorize the instruction and apply it at the appropriate waypoint (1 min, 3 min, or 5 min later). The trial terminated after 7 min. At the end of each trial, participants were prompted to recall the three airplanes and the associated waypoints for which alternative instructions were issued. After they completed the recall test, a message to press a key to continue was displayed on the screen. All participants completed one practice and 12 experimental trials. The practice trial was intended to familiarize the participants with the foreground task. It was similar to the experimental trials, except that it did not contain prospective memory instructions.

Results

Recall performance. For each participant proportion of instructions correctly recalled were scored as a function of load and delay between receiving a prospective instruction and executing that instruction. Recall was scored as erroneous if the participant incorrectly named either the airplane, the waypoint, or both. These data were analyzed using within-participants ANOVA with load and delay as variables. Recall was significantly worse with high workload (F (1,27) = 19.60, p < .01). Delay did not produce a significant effect (F (2,54) = 1.25, p = .29). No significant interaction was observed (F (2,54) = 1.26, p = .30). Table 1 shows mean proportion of correctly recalled instructions as a function of load and delay.

[Table 1 about here]

Prospective memory performance. For each participant, prospective memory errors were computed as the proportion of prospective memory instructions for which the airplane was highlighted and directed to the default routine waypoint instead of the alternate. These results are summarized in Table 2. Only cases in which both the airplane and the waypoint to which it was diverted were correctly remembered at the end of the trial were included)—this precluded failures of retrospective memory from being counted as prospective memory errors. However, as it turned out, analysis of prospective memory errors regardless of whether instructions were remembered at the end of the trial revealed virtually identical results (data not shown).

[Table 2 about here]

Errors were analyzed in a two-way within-participants ANOVA with delay and load as variables. The only significant effect was that of load (F (1,27) = 17.90, p < .01), which reduced prospective memory performance. All other F's < 1. In the low load condition few errors were made, which conceivably could have reduced sensitivity to manipulations.

Foreground task performance. We defined foreground task performance in terms of correctly sending airplanes on to their next waypoint whenever a diversion to an alternate waypoint was not required. Participants could fail to execute a correct response by failing to click on an airplane while in the response window, by failing to click on the next waypoint, or by incorrectly selecting an alternate waypoint when an alternate was available. For the majority of airplanes to which no prospective instruction pertained (“routine airplanes”), all waypoints were used to calculate the percent of correct responses. For airplanes for which a prospective instruction was given (“divert airplanes”), the waypoint at which the participant was instructed to select the alternate was excluded from this calculation. For each participant the proportion of correct responses was computed separately for routine and divert airplanes and for high and low workload trials.

Participants performed better with routine airplanes (airplanes with no alternative destinations) than with divert airplanes for both low workload trials (t (27) = 2.0, p = .055) and high workload trials (t (27) = 4.68, p < .01) workload trials. Thus, having to keep a prospective instruction in mind for a particular airplane reduced foreground task performance even though the instruction did not pertain to the foreground task. In addition, performance was better in low workload trials for both routine airplanes (t (27)

= 3.07, p < .01) and divert airplanes (t (27) = 5.23, p < .01) airplanes. The means and standard deviations are presented in Table 3.

[Table 3 about here]

Experiment 1b

In Experiment 1a, we obtained an effect of workload both on performance of the foreground task and on prospective memory performance. Thus, so far, prospective memory performance suffered when performance on the foreground task suffered. It would be even more interesting if we could find factors that affect prospective memory performance but leave performance on the foreground task intact. The goal of Experiment 1b was to examine the role of verbal rehearsal on both types of performance. We hypothesized that blocking verbal rehearsal might reduce prospective memory performance without affecting routine task performance. We intentionally designed our experimental paradigm so that the foreground activity was visual-spatial rather than verbal in nature. Thus the foreground task should be minimally dependent on verbal rehearsal, in contrast to verbal paradigms. However, participants in Experiment 1a might have chosen to rehearse the prospective instructions verbally, especially since they had to remember up to three instructions, each specifying an airplane and a waypoint. In Experiment 1b we repeated the manipulations of Experiment 1a and also required participants to shadow an auditory message to block verbal rehearsal.

Method

Participants. Twenty student volunteers from local community colleges and a state university, 18-40 years old, participated and received credit for their participation.

Apparatus, display, design, trial sequence, and task. All of these were the same as in Experiment 1a. The auditory message was played on a cassette player and presented via headphones to the participants.

Procedure. The procedure was identical to that of Experiment 1a, except that participants were also required to continuously shadow (repeat aloud) an auditory message presented via headphones to them. The text of the message came from a recent Newsweek article and was recorded.

Results

Recall performance. Recall errors were scored as a function of load and delay between instruction and execution of the prospective memory command for each participant. These data were analyzed using within-participants ANOVA with load and delay between instruction and execution time as variables. Recall was worse with higher load (F (1,19) = 19.65, $p < .01$), but no effect of delay was observed (F (2,38) < 1). No significant interaction was observed (F (2,38) < 1). Table 4 shows mean proportion correct as a function of load and delay.

[Table 4 about here]

Prospective memory performance. Error computation for each participant was identical to that in Experiment 1a. These results are summarized in Table 5.

Errors were analyzed in a two-way within-participants ANOVA with delay and load as variables. Performance was worse with higher load (F (1,19) = 4.97, $p < .01$). No other significant effects were observed (F's < 1).

[Table 5 about here]

Foreground task performance. Participants performed better with routine airplanes than with divert airplanes in both low (t (19) = 2.1, p < .01) and high workload trials (t (19) = 4.88, p < .01). In addition, they performed better in low than in high workload trials with both routine (t (19) = 6.39, p < .01) and target (t (19) = 6.60, p < .01) airplanes. The means and standard deviations for proportion of correctly completed responses are presented in Table 3.

Combined Analysis of Experiments 1a and 1b

Even though Experiment 1a preceded Experiment 1b chronologically by about 1 year, participants for both experiments were drawn from the same populations, and differences in task performance are most likely not due to participant characteristics, but rather due to the experimental manipulation (verbal shadowing task) used in Experiment 1b. Thus, we conducted combined analysis of data from Experiments 1a and 1b to determine the effect of verbal shadowing on task performance and its interactions with our other two manipulations – workload and delay.

Recall performance. The data were analyzed using a mixed variable ANOVA with load and delay between instruction and execution time as within-participants variables, and experiment (Experiment 1a, no secondary verbal task, versus Experiment 1b, secondary verbal task) as the between-participants variable. The effect of experiment was significant (F (1,46) = 18.48, p < .01), and the effect of load was significant (F (1,46) = 41.67, p < .01). Significant interaction occurred between experiment and load (F (1,46) = 4.74, p < .01). Thus both high load and lack of opportunity for rehearsal reduced recall of prospective memory instructions, and their effects were greater than additive. No effect of delay or interaction between delay and experiment occurred (F 's (2,92) < 1).

There was a trend towards an interaction between load and delay; at higher load recall appeared to be better for 3' and 5' instructions than for 1' instructions (F (2,92) = 2.93, p < .06). No three-way interaction was present (F (2,92) < 1).

Prospective memory performance. Errors were analyzed in a mixed variable ANOVA with delay and load as within-participants variables, and experiment as the between-participants variable. There was a significant effect of experiment (F (1,46) = 4.52, p < .01) and load (F (1,46) = 18.69, p < .01); both articulatory suppression and load reduced performance. All other effects were non-significant (F's < 1).

Foreground task performance. The data from foreground task performance were analyzed using mixed variable ANOVA with experiment as a between-participants variable and load (high, low) and type of airplane (routine, target) as within-participants variables. There was no significant effect of experiment (F (1,46) < 1), which suggests that the foreground task placed no verbal demands and did not require phonological rehearsal. Both load (F (1,46) = 82.22, p < .01), and type of airplane (F (1,46) = 16.96, p < .01) produced effects. Foreground task performance was consistently worse with high load and with divert airplanes. The interaction of load and experiment was significant (F (1,46) = 4.07, p < .05); surprisingly, the participants in Experiment 1b (shadowing) performed better than participants in Experiment 1a on low workload trials. The interaction of load and type of airplane was significant also (F (1,46) = 4.88, p < .05); high workload affected foreground task performance with divert airplanes more than with routine airplanes.

General Discussion

We have developed a new paradigm that allows prospective memory studies to be extended to situations in which intentions, cues, and actions are defined in terms of dynamic visual-spatial parameters. This paradigm has several useful features:

(I). It allows repeated measures of prospective memory performance within participants, providing different instructions in each instance. In most prospective memory paradigms the participant is given only a single prospective memory instruction (e.g., “press a key when you see one of these words”) and may encounter the target words several times.

(II). The prospective task is closely and meaningfully linked to the ongoing foreground task. This arrangement corresponds to an important class of real-world situations in which individuals must remember to deviate from habitual actions under certain conditions. This contrasts with most laboratory paradigms in which the foreground task is a cover task unrelated to the prospective task, other than providing cues for execution.

(III). It uses a window of opportunity for executing intentions that is more complexly defined than the simple occurrence of a word. In real-world situations a wide range of environmental conditions may define the window of opportunity for executing an intention, and cues for remembering may include events, objects, the location or activity of the individual, or some combination of these (Ellis, 1996).

Although this paradigm offers certain advantages, programming and data analysis are more complex than with conventional paradigms using verbal materials.

In our first application of this paradigm, we examined the effects of load and phonological rehearsal on prospective memory performance over a range of relatively short delays in two experiments. Workload was manipulated by changing the number of airplanes simultaneously on the screen (low: 3 airplanes; high: 7 or 8 airplanes). Thus, on high workload trials participants had to keep track of more airplanes, and the rate of responding required was substantially higher. Our manipulation of workload was effective since it reduced performance on the foreground task of directing airplanes along the default circuit of waypoints. The demands of the foreground task appear to be nonverbal, since the performance on this task was not affected by the manipulation that prevented phonological rehearsal.

In our paradigm, at certain waypoints the display gives participants a choice between two options. Even under low workload conditions and without shadowing, participants failed to execute prospective memory instructions (which they were later able to recall) in 7 to 8% of the opportunities. These errors seem to represent a form of habit intrusion in which the participants automatically selected the usual default waypoint without retrieving the intention to divert the aircraft.

Our data indicate that increasing workload and preventing phonological rehearsal of instruction increased errors in delayed execution of prospective memory instructions. (Data were computed only for instructions correctly recalled after the trial). Varying delay between 1 and 5 min did not increase prospective memory errors. Recall of prospective instructions at the end of the trials was also reduced by increasing workload and by blocking phonological rehearsal. In high workload conditions there was a trend

($p < .06$) for prospective instructions that were to be executed in 1 min to be recalled less well than instructions that were to be executed in 3 min or 5 min.

Our findings suggest that prospective memory performance at short delays with this dynamic visual-spatial task is a function of working memory. These findings are consistent with studies using a verbal paradigm that found dividing attention at retrieval reduces prospective memory performance (Einstein, McDaniel, Smith, & Shaw, 1998; Einstein, Smith, McDaniel, & Shaw, 1997; McDaniel, Robinson-Riegler, & Einstein, 1998). Attention was divided in these verbal-paradigm studies by requiring participants to monitor a series of auditorally presented digits for the occurrence of two or three consecutive odd digits, in addition to a concurrent task such as pleasantness rating. However, our results conflict with studies in which articulatory suppression did not alter prospective memory performance (Marsh & Hicks, 1998; Otani et al., 1997). The difference in our findings might be explained by the nature of our prospective memory task and its relation to the foreground task of routing airplanes to their routine destinations. During the course of a trial participants had to remember concurrently three prospective memory instructions (given verbally), each with two components – airplane and waypoint. Participants probably chose to rehearse these sub-vocally when it was possible. Our foreground task did not require remembering verbal material, and thus was not affected by articulatory suppression. In contrast, Marsh and Hicks and Otani et al. used short-term memory tasks as foreground tasks, and performance on these short-term memory tasks was lowered by articulatory suppression. Thus participants in their experimental paradigms may not have been able to use phonological rehearsal for the prospective memory task because of the demands of the concurrent short-term memory task.

Marsh and Hicks (1998) found that increasing demand on the central executive component of working memory decreased prospective memory performance. It seems likely that our manipulation of workload and the manipulation used by Einstein, McDaniel, and colleagues increased the demands on the central executive. Thus, the various studies seem to agree on at least this one point.

In our paradigm, the workload manipulation cut across encoding, retention, and retrieval, and we cannot tell to what extent the effect of the manipulation was due to effects on retention versus retrieval. Since prospective memory errors were computed relative to remembered instructions only, the effects of workload on prospective memory in our study can be narrowed down to retention and/or retrieval.

Our findings are consistent with verbal paradigm studies in which increasing retention interval from 4 to 20 minutes (Guynn, et al., 1998) or from 15 to 30 minutes (Einstein et al., 1992) did not affect prospective memory. In contrast, Brandimonte and Passolunghi (1994) found decreased prospective memory when retention interval increased from 0 to 3 minutes, which is consistent with the effects of delay in studies of retrospective memory. However, Hicks, Marsh, and Russell (2000) found improved prospective memory when the retention interval was increased from 2.5 to 15 minutes. They cite evidence that pending intentions may be maintained in an activated state and speculate that longer delays may provide opportunities to remember the intention during momentary pauses in the foreground task.

Two aspects of our paradigm may have contributed to the lack of effect of delay. Testing for recall at the end of each trial may have enhanced the salience of the prospective memory aspect of the experiment. Also the three delay intervals partially overlapped, so that the participants had to remember more than one instruction during some moments of the trial. Thus, the multiple instructions may have reinforced each other.

Given the different ranges of retention interval and the different tasks used in this and previous studies, clear conclusions about the effect of delay on prospective memory cannot be drawn.

An intriguing finding in our study is that participants made more errors on the foreground task (sending airplanes to the routine default waypoints) with divert airplanes than with routine airplanes. It may be that participants hesitated as they tried to remember whether the upcoming waypoint was the one for which the target airplane was to be diverted and either failed to click on the airplane while it was in the window or mistakenly diverted it. This suggests that associations with an object pertaining to manipulating it in one task may interfere with correctly manipulating the object in another task for which the associations are not relevant.

In our paradigm, manipulations of workload and phonological rehearsal had similar effects on execution of those prospective memory instructions that were correctly recalled and on the number of instructions that were recalled at the end of trials. Einstein and McDaniel (1996) characterized prospective memory as having a prospective component and a retrospective component. We would couch this distinction as follows: Intentions are presumably stored in memory as nodes, with slots for action to be taken, object of the action, and conditions under which the action is to be taken (the window of opportunity). The prospective component has to do with whether the intention is retrieved into focal attention. The retrospective component has to do with the content of the slots. (Note that not all of the slots are always retrieved; for example, one may remember intending to call someone, but not remember who was to be called). Our data indicate that in our paradigm the prospective and the retrospective components of prospective memory respond similarly to manipulations of workload and phonological rehearsal.

Our data also suggest that it is desirable for practical and theoretical reasons to develop an array of prospective memory paradigms to explore the range of retrieval contexts and the interaction of cognitive processes that support both prospective memory and foreground task performance. In particular, performance of prospective memory tasks may depend on the relation of the prospective task to the foreground task in which it is embedded. Variations in demands of the foreground task are likely to affect availability of limited resources for the prospective task. Furthermore, the moment-to-moment operations of the foreground task may create cues or direct the individual’s attention to environmental cues that trigger retrieval of the intention through pre-existing associations. Conversely, the foreground task may direct the individual’s attention away from cues that might support retrieval of the intention – this is an especially critical issue in many real-world situations.

Our findings may have important practical implications because they demonstrate that certain secondary tasks and distractions (e.g., verbal shadowing) may not be problematic for performance of some habitual tasks, but become problematic when occasional special instructions to deviate from habit must be remembered and executed at a later time. This may be particularly dangerous because the ability to cope with a routine set of habitual actions while carrying on other tasks, such as casual conversation, does not necessarily imply the ability to remember and cope with unusual situations under the same conditions.

Gromelski, Davidson, and Stein (1992) interviewed a large number of air traffic controllers and found that half of them had experienced one or more memory lapses that resulted in two aircraft coming into unacceptably close proximity in flight. Stein and Garland (1993) concluded that working memory is a critical bottleneck affecting the performance of controllers in high workload conditions. Our study illustrates some of ways in which working memory demands might influence the performance of controllers and other personnel performing dynamic visual-spatial tasks.

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Author Note

Maria Stone. Mail Stop 262-4. NASA-Ames Research Center, Moffett Field, CA 94035.

Key Dismukes. Mail Stop 262-4. NASA-Ames Research Center, Moffett Field, CA 94035.

Roger Remington. Mail Stop 262-4. NASA-Ames Research Center, Moffett Field, CA 94035.

Correspondence regarding this manuscript should be addressed to Key Dismukes at the address above or via e-mail at kdismukes@mail.arc.nasa.gov. We thank Miri Gold, Mike Shafto, and Grant Young for helpful discussions of this project, Brett DeSchepper for writing the computer program for generating these experiments, and Wallace Henry for help with data collection and analysis.

Footnote

[1] In this paper we use the term “foreground task” to emphasize that on-going task activities, strongly supported by environmental cues and demands, are in the forefront of the participant’s attention.

Table 1.

Proportion of Prospective Memory Instructions that Were Correctly Recalled at the End of Each Trial in Experiment 1a.

	Mean Correct	Standard Deviation
Low Load		
Delay 1 Minute	.92	.12
Delay 3 Minutes	.92	.10
Delay 5 Minutes	.93	.13
High Load		
Delay 1 Minute	.80	.17
Delay 3 Minutes	.87	.17
Delay 5 Minutes	.85	.17

Table 2.

Proportion of Prospective Memory Execution Errors Relative to Correctly Recalled Instructions at the End of Each Trial Experiment 1a.

	Mean	Standard Deviation
Low Load		
Delay 1 Minute	.08	.14
Delay 3 Minutes	.07	.13
Delay 5 Minutes	.08	.17
High Load		
Delay 1 Minute	.17	.23
Delay 3 Minutes	.20	.26
Delay 5 Minutes	.22	.24

Table 3.

<u>Mean Proportion of Correctly Completed Responses (Standard Deviations) in the Routine (Foreground) Task in Experiments 1a and 1b.</u>

	High Workload	Low Workload
Experiment 1a		
Routine Airplanes	.72 (.12)	.77 (.09)
Divert Airplanes	.60 (.16)	.70 (.09)
Experiment 1b		
Routine Airplanes	.70 (.09)	.81 (.06)
Divert Airplanes	.63 (.09)	.76 (.07)

Table 4.

Proportion of Prospective Memory Instructions that Were Correctly Recalled at the End of Each Trial in Experiment 1b.

	Mean Correct	Standard Deviation
Low Load		
Delay 1 Minute	.82	.16
Delay 3 Minutes	.79	.21
Delay 5 Minutes	.80	.23
High Load		
Delay 1 Minute	.59	.26
Delay 3 Minutes	.67	.25
Delay 5 Minutes	.64	.24

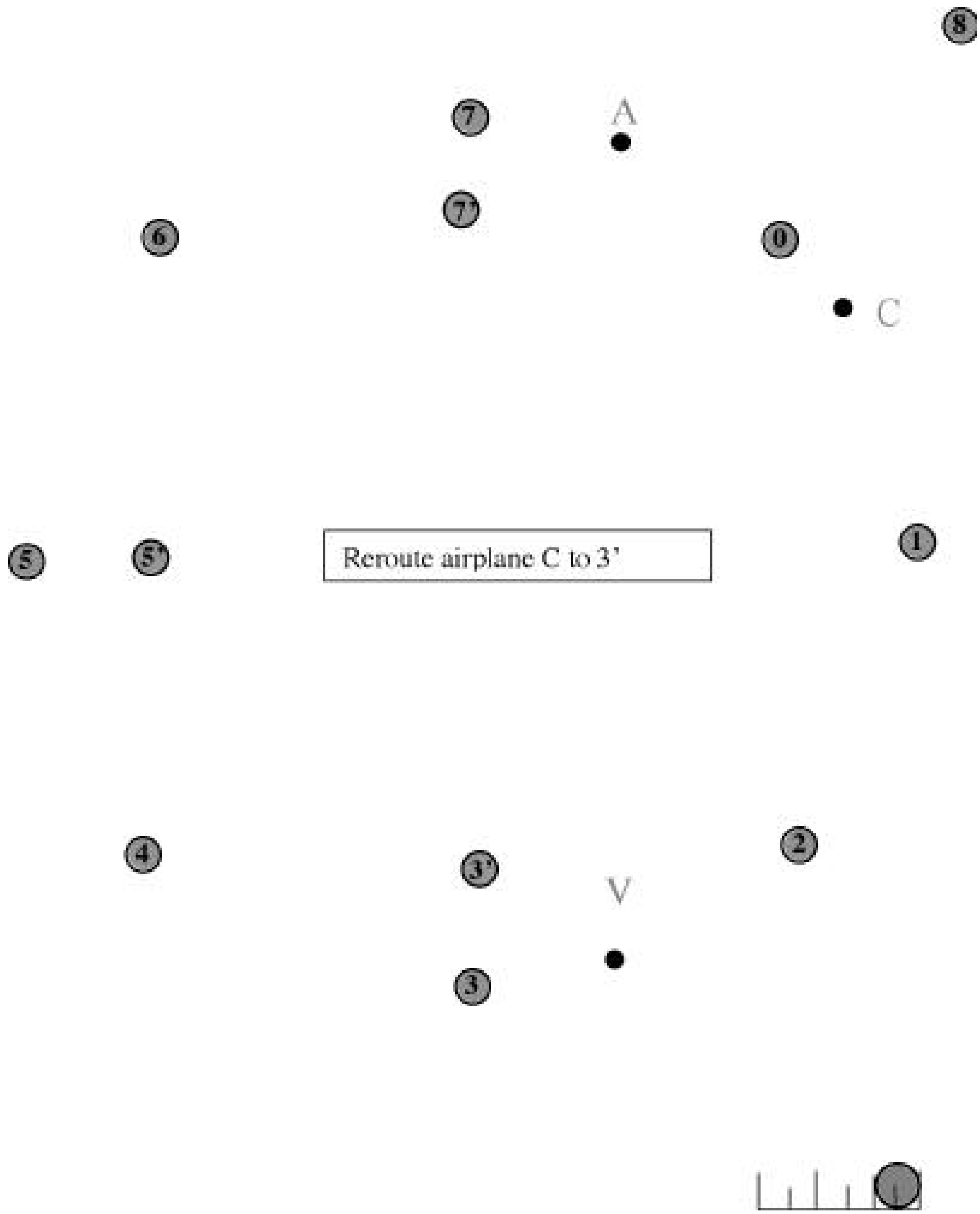
Table 5.

Proportion of Prospective Memory Execution Errors Relative to Correctly Recalled Instructions at the End of Each Trial in Experiment 1b.

	Mean	Standard Deviation
Low Load		
Delay 1 Minute	.20	.26
Delay 3 Minutes	.17	.26
Delay 5 Minutes	.20	.27
High Load		
Delay 1 Minute	.29	.33
Delay 3 Minutes	.28	.33
Delay 5 Minutes	.34	.35

Figure Caption

<u>Figure 1.</u> Sample display for Experiments 1a and 1b.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